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DUDLEY OBSERVATORY RADIO TELESCOPE PROJECT.(U)
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ABSTRACT

During the period from July 1, 1971 to June 30, 1976 the Dudley Observatory was supported by the Office of Naval Research under Contract Number N 00014-72-C-0040. During that period the observatory began and completed construction of its 100-foot diameter radio telescope and associated electronics, and initiated work, with the support of the National Science Foundation, on a coherent FFT-based spectrometer. This document contains summaries of the work done over the contract period in four major areas: telescope design and construction, electronics design and construction, signal processing theory and science. In addition, this document contains appendices in which reprints of several published articles and astracts appear.

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Telescope Summary

General

Dudley Observatory completed work on its 100-foot diameter radio telescope in July 1975. The instrument, built largely with funds raised through private subscriptions, was dedicated as the Frank L. Fullam Radio Telescope, in honor of the father of one of the principal benefactors.

The Dudley Observatory Radio Telescope Project has been supported by the Office of Naval Research under Equipment Loan Contract N 00014-72-C-0040. Under the equipment loan contract the observatory acquired a surplus twin 5"-38 gun mount (for use as an azimuth bearing for the radio telescope) as well as some auxiliary equipment (20 ton crane, 2½ ton truck, etc.) used in the construction (and subsequent operation) of the instrument.

The Parabolic Reflector and Feed System

A 100-foot diameter parabolic reflector, shown in Figure 1, ($\frac{f}{D} = 0.41$) was donated by the Carnegie Institution of Washington (Department of Terrestrial Magnetism). The paraboloid, originally located in Derwood, Maryland, was disassembled, trucked to its new site near Bolton Landing, New York, and reassembled. The dish was stiffened and strengthened through the addition of more structural members, and a new expanded aluminum hex-mesh surface was installed. With these modifications the dish can be used at wavelengths as short as 6 cm. At that wavelength,

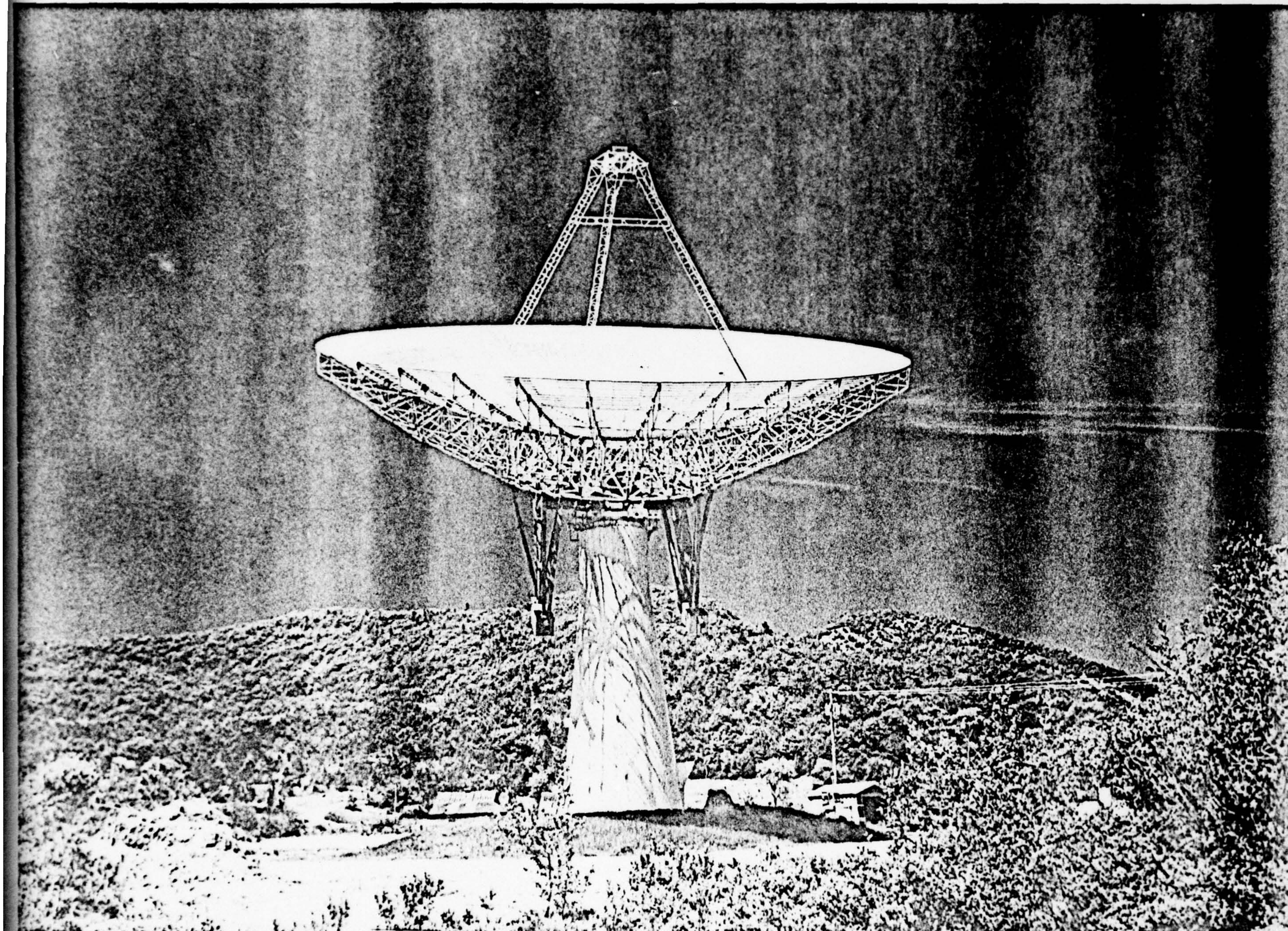


Figure 1. Frank L. Fullam Radio Telescope

mesh leakage should be $\sim$ 3% with a surface accuracy of $\sim$ 1/20 at the zenith, falling off somewhat with increasing zenith angle because of gravitational deformations. Since the present observational program involves coherent observations at 92 cm λ, the paraboloid's performance is excellent, and no degradation with zenith angle can be detected.

The paraboloid is fed at the prime focus. Three feed legs support a space frame which contains the hardware to support, and remotely focus the radiometer. The feed antenna for the 92 cm λ system is a pair of cross-polarized dipoles supported over a ground plane; a quadrature coupler is used to produce circularly polarized radiation. Response of the feed system is down by $>$ 15db at the edge of the parabola to reduce side lobes.

The Support Tower and Mounting System

An altitude-azimuth design by Neil Stafford of the Stanford Research Institute was used to support the parabolic antenna. The 5" -38 caliber twin gun mount obtained through ONR was used as a precision azimuth bearing. Altitude motion is being provided by a commercially obtained recirculating-ball jack screw. The gun mount sits on a conical steel tower 50' high and 20' in diameter at the base.

The tower, built of deeply flanged 5/16" steel plate, has been subdivided into five floors. The lowest floor is a machine shop area,

while the second floor is used for the telescope control room. Floors three and four are used for storage; the top floor is the location of the hydraulic power unit for the telescope's drive system. The radiometer cables, both RF and power, drop from the upper stories to the ground floor through a 4-foot square well area in the center of each floor. A power-winch system utilizes the same well for moving heavy equipment (equipment racks, etc.) from floor to floor. A torque-tube interface provides the link between the elevation bearings on the gun mount deck and the parabolic structure.

Finally the entire structure rests on a 240 ton reinforced concrete foundation. Because of high ground water in the locale, the foundation rests on better than 500 tons of crushed rock; this scheme, similar to those used in artic regions, eliminated the possibility of frost heave.

The salient features of the telescope's mounting system can be seen in Figures 2 and 3.

The Drive and Pointing System

As a means of reducing the cost of the drive system, an open-loop system featuring electrohydraulic digital steeping motors was chosen instead of the more conventional closed-loop servo system with analog hydraulic motors. (The open-loop system hinges on the accuracy of the stepping motors, and eliminates the necessity for extremely accurate

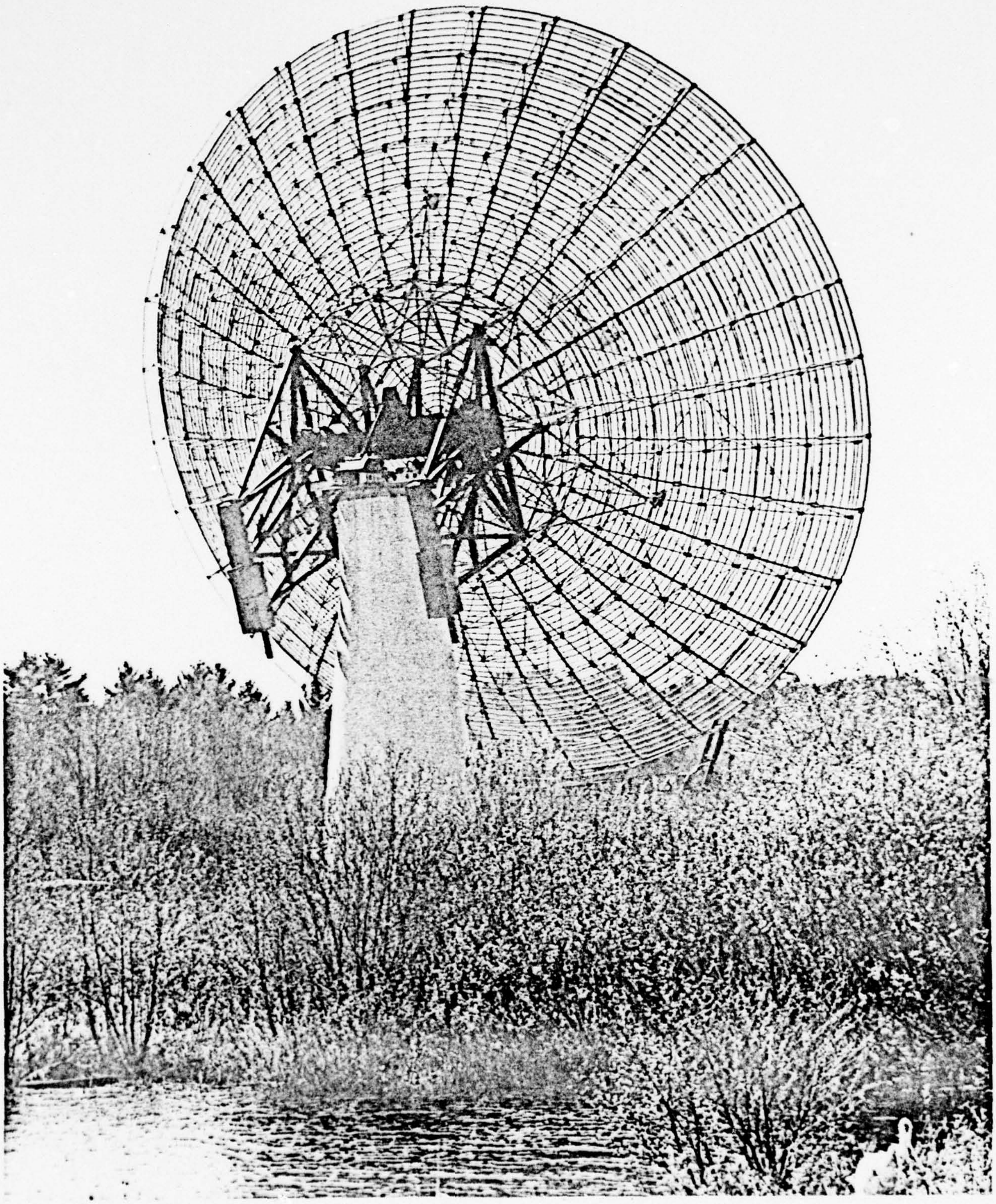


Figure 2. The Frank L. Fullam Radio Telescope

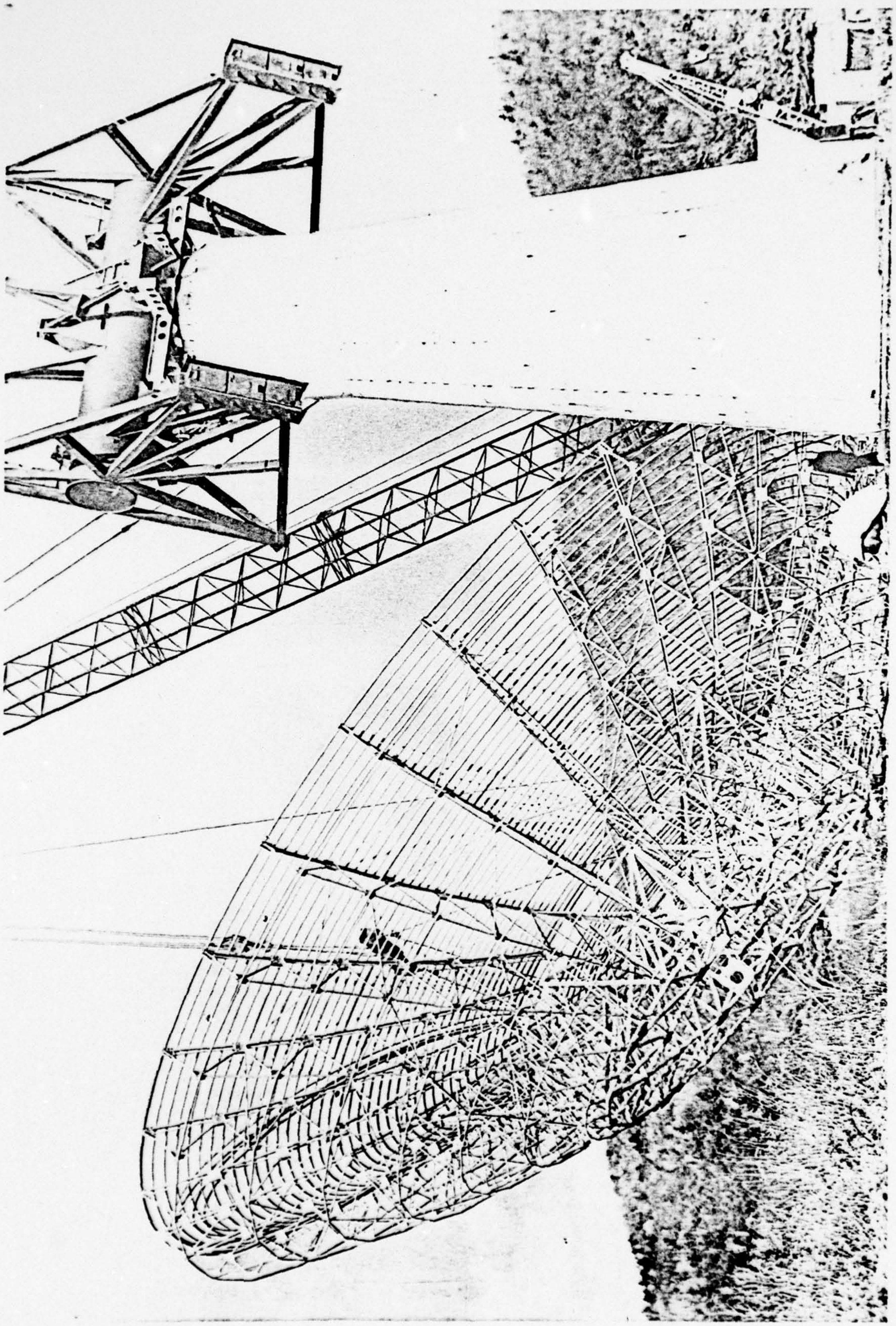


Figure 3. The Mounting System During Construction

shaft encoders). At the time, the cost of optical shaft encoders with the required accuracy was ~ $20,000 a piece; since then the dramatic drop in optical encoder prices has reduced the cost advantage of the open-loop design.

A group of graduate and undergraduate students at R.P.I. under the direction of Professor Dean Frederick and I worked on the details of the system. The group did detailed calculations of the moments of inertia in a variety of orientations and situations (wind loading, snow loading, etc.), and recommended gear ratios, motor sizes, etc. for the system. It incorporates electrohyraulic stepping motors (4 H.P. at 3000 RPM) for each coordinate. The motors produce relatively constant torque from 0 to 3000 RPM and are used for both tracking and slewing. At slew, they can move the telescope at a rate of better than 20°/minute in each coordinate, while maintaining positional accuracy of one arc-minute.

The necessary coordinate conversions (celestial to horizon system) are performed by a dedicated Microdata 1600/21 mini-computer. The computer generates altitude and azimuth rates once each ten second; an external digital interface converts the rates into smooth phase-locked pulse trains which are fed to the altitude and azimuth drive motors. The computer provides other useful services such as automatic pointing corrections, as well as incorporating software safety limits to prevent damage to the instrument.

In addition two levels of hardware safety limits have been

added for each coordinate, greatly increasing the safety margin.

Use of the instrument is simple and convenient. The operator sits at a CRT terminal, and types in the coordinates of the sources that he wishes to track. After the positions are entered the computer takes over and slews the telescope to the proper position and begins tracking. If he has chosen an unsuitable source, (perhaps a source which has set), it warns him, and waits for new instructions. The interactive software is helpful in reducing operator error.

The drive system has ben fully tested and is capable of accurately positioning the telescope and tracking celestial sources over the entire visible sky, (except for sources near the zenith - here the azimuth rates go through a singularity; for these sources the telescope will wait for further instructions - eg. another source).

Electronics Summary

Radiometers

Our first radiometer, operating at 21 cm was put together in 1975, and used for telescope evaluation purposes. The RF section was a surplus Western Electric wideband dual stage paramp which we modified extensively. We were able to reduce its band pass to $\sim$ 50MHz, increase the gain to $>$ 25db, and to improve its noise figure considerably. The system noise temperature with a diode switch before the paramp was $\sim 120^{o}$K.

The 92cm λ radiometer being used presently was constructed

in 1975-1976. It is designed with phase linearity and stability in mind (in keeping with the coherent signal processing experiments we are conducting) and employs transistor amplifiers for the RF stages. Since our experiments involve observations in the galactic plane (where the cosmic noise component is strong) low system noise temperature is not crucial. In order to reduce its cost, inexpensive components were used; as a result the system noise temperature is not impressive ($T_{sys} \sim 250^{o}K$). It does however have the phase linearity and stability which are required.

Analog Signal Processing Hardware

The rest of the analog signal processing electronics were completed in late 1975. The analog system prepares the IF signal for later coherent digital signal processing by down-converting the 30MHz IF signal to baseband. Matched in-phase and quadrature components are created, for input to the digital signal processor, and in general, phase linearity and stability is maintained. A schematic of the IF signal processing system can be seen in Figure 4.

Digital Signal Processing Hardware

The digital signal processing system used on the Fullam Telescope was designed and built by the observatory staff in collaboration with Ivan Linscott of Syracuse University and Noble Powell of the General Electric Company's Electronics Laboratory. The development was

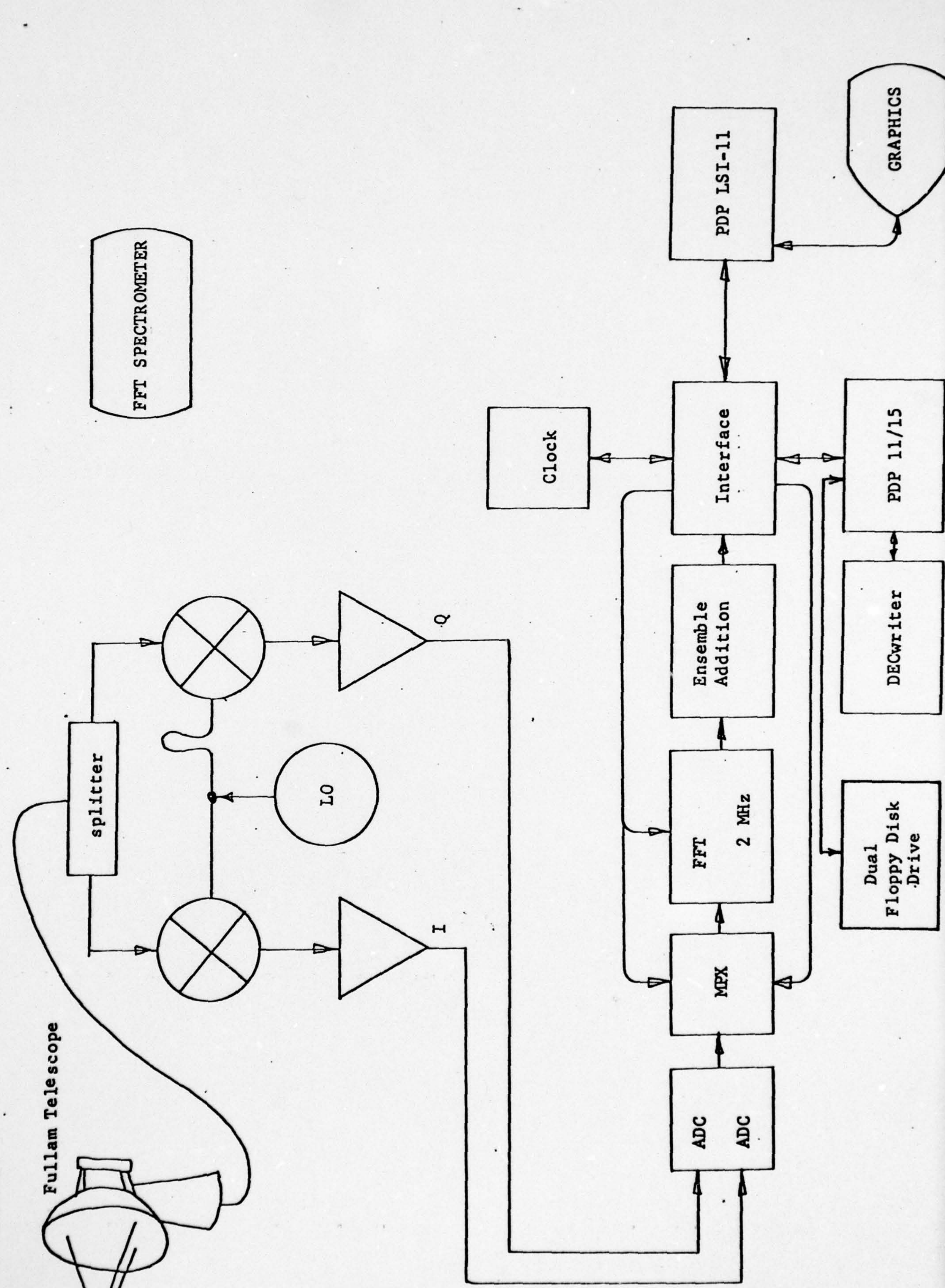
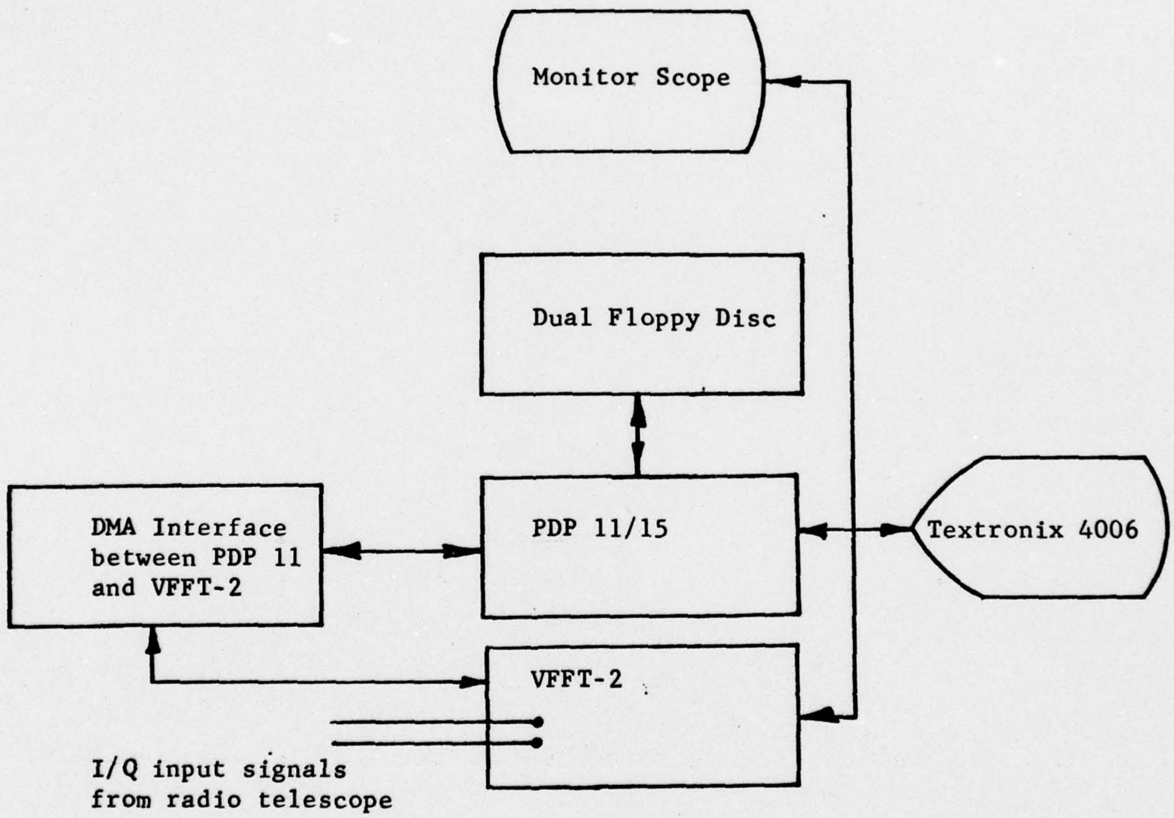

FFT SPECTROMETER
Fullam Telescope
splitter
LO
Q
I
ADC
ADC
MPX
FFT
2 MHz
Ensemble
Addition
Interface
Clock
PDP LSI-11
GRAPHICS
PDP 11/15
DECwriter
Dual
Floppy Disk
Drive

Figure 4

supported by the National Science Foundation, under NSF Grant AST75-23394. As can be seen in Figure 4, matched 2MHz ADC's feed the in-phase and quadrature input ports of a real-time 2MHz Fast Fourier Transform (FFT) digital processor. The FFT processor* computes, in real-time, complex 1024 pt frequency spectra with 12 bits of precision, processing continuously digital time series into frequency spectra at a rate of 4 million (12 bit) words/second. The frequency spectra thus produced are made available through a DMA port to a PDP11/15 computer for analysis and display. An important feature of the system is that spectra generated or modified by the computer can be recursed through the FFT processor. As a result, deconvolutions of several important classes of signal distortions can be implemented in real-time. The system is versatile and can be used for off-line analysis and display as well as for the real-time capture and analysis of cosmic data. A photograph of part of the completed digital processing hardware can be seen in Figure 5a and 5b.

* The FFT processor is based on new, cost effective technology developed by G.E.'s Electronics Laboratory, and is only the first step in the development of digital processor with wider bandwidths and/or more channels; by this spring for example we will have an operational 10MHz 1024 pt (complex) FFT processor.



I - in-phase or real signal (proportional to Cos ωt)
Q - quadrature signal (proportional to Sin ωt)

Figure 5a - Fast Fourier Transform Spectrometer-- 2 MHz Bandwidth, Real Time Monitor, Dispersion Spectrum Capability, Installed at Dudley Observatory's Frank L. Fullam Radio Telescope

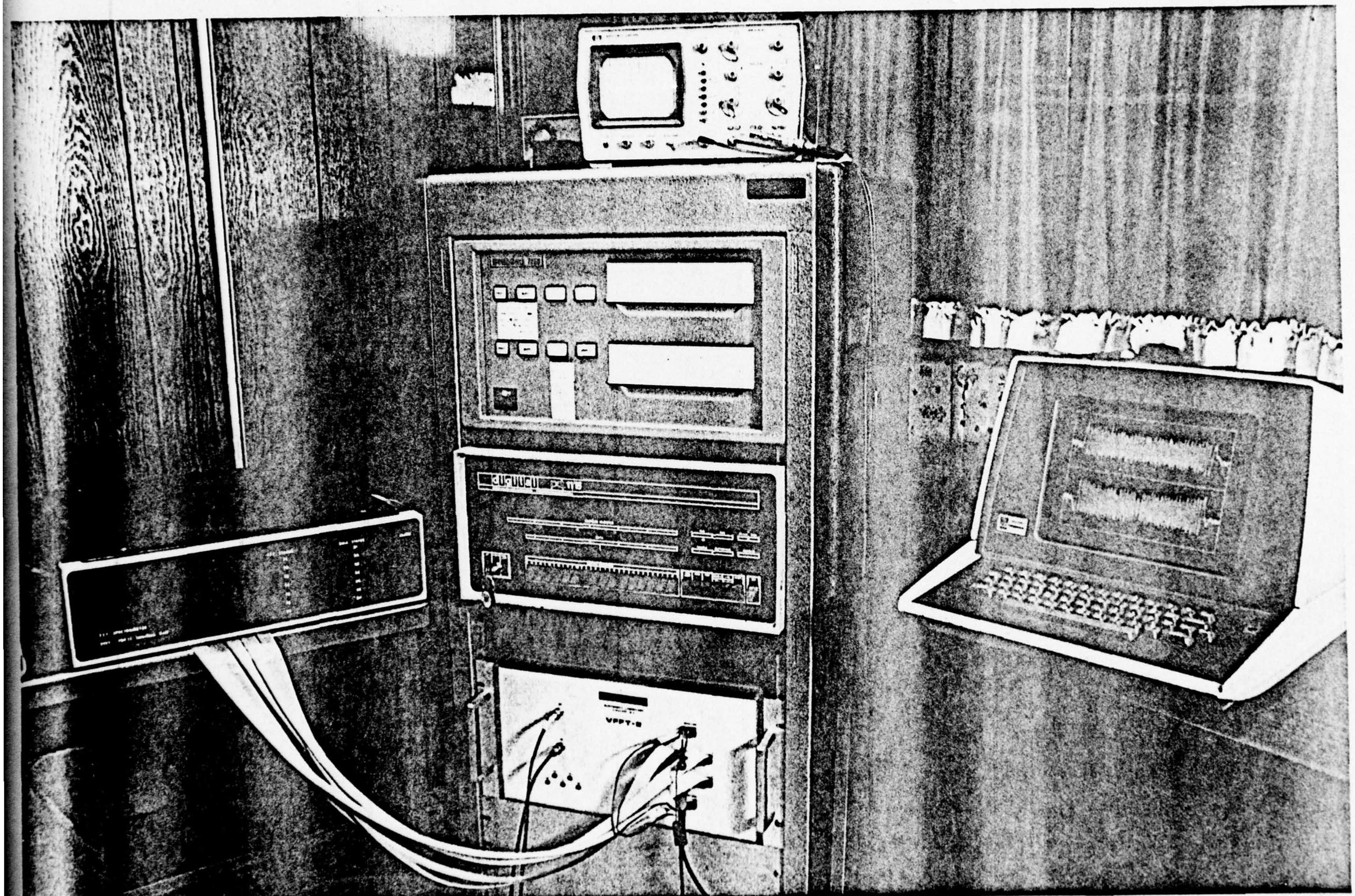


Figure 5b FFT Spectrometer

Signal Processing Theory Summary

The signal processing hardware outlined in the previous section was constructed to permit the flexible manipulation of the amplitude and phase of signals received by the radio telescope. We are using this equipment at present to probe alternative schemes for the reconstruction of highly dispersed electromagnetic signals. Cosmic electromagnetic waves propagating through the weak interstellar plasma suffer deep dispersive distortions; in particular, waves which are deeply modulated in time (e.g. pulses) become, as a direct result of dispersive distortions, highly smeared in time, and greatly attenuated. Signal to noise (S/N) degradations of 10^6 are not unreasonable for pulses from the center of our galaxy, along with a loss of detail in the time structure by comparable factors.

A new technique for the on-line removal of these dispersive distortions for deeply modulated waveforms has been developed. The implementation of this technique in the study of pulsed waveforms is a dispersion spectrum (described in Appendix A), and has several important advantages over other dispersion compensation schemes. Briefly, the scheme offers S/N improvements of a factor of 100 over post-detection compensation schemes (see e.g. Hankins, 1975), and has the further advantage that the amount of dispersion (or the distance to the pulse source)need not be known a priori. It is therefore an effective real-time coherent pulse filter, and can be used to search for asynchrous coherent pulses buried in the cosmic noise background.

Since dispersion distortion is a common phenomena in the propagation of waves in other media, these new techniques have wide applicability beyond radio astronomy; it is not difficult to imagine their use in seismology, sonar signal processing, ultrasonic tomography, and a host of other fields.

Science Summary

The 2MHz prototype FFT Spectrometer system described above has been interfaced to the Fullam Telescope and an observational program capitalizing on its peculiar advantages has been initiated. Prime targets are the pulsars (examples of synchronous pulse emission) and the globular clusters (examples of asynchronous x-ray pulses, and perhaps radio pulses as well).

Pulsars

The radio signal from pulsars has a strong microstructure. The microstructure characteristically shows strong fluctuations in intensity on a time scale that is still unresolved. Using dispersion removal in the wide bandwidth of the spectrometer will permit the study of microstructure on a much finer time scale (down to 100 nsec.). This capability will provide the best chance yet to understand the nature of the pulsar emission mechanism.

By removing dispersion in real-time, individual pulses can be examined, and a directory of interesting, or unusual pulses can be constructed. In this manner, physical models of the pulsar emission

mechanism may be tested, and new features of the pulsar signals may be discovered.

The higher sensitivity inherent in this instrumentation will be useful in searching for pulsars that are too faint to be seen using present techniques. In fact, bright pulsars in nearby galaxies may be seen for the first time. If pulsars are found in other galaxies, their distribution within the galaxy may be measured. The spatial distribution of the pulsars is important in determining the nature of galactic evolution.

The signals from pulsars suffer distortions as they propagate through the tenuous gas that comprises the interstellar medium. By unfolding these distortions from the pulsar signals, the nature of the distortion mechanism may be studied. Thus, the pulsars are excellent probes of the interstellar material, and may be used as tools for the study of the interstellar medium.

Radio Burst Search from Globular Clusters

The real-time dispersion removal and computation of the dispersion spectrum capability that the FFT Spectrometer features enables sporadic radio bursts to be discovered. For example, if a source located deep in the galaxy occasionally omits pulses of microwaves, the pulses would be so broadened by the distortions suffered in traveling through the interstellar material, that they would be too faint to be

detected on arrival. By removing the dispersion distortion in real-time, the pulse is approximately restored to its original shape and becomes much stronger, and thus detectable. Further, the real-time aspect of the signal processing guarantees that the pulse would be detected whenever it came in. So a source that emits pulses sporadically could be seen and identified. The globular clusters, particularly old ones, are very likely sources of sporadic, microwave bursts. Other sites of high stellar density, such as the galactic center, are also good candidates for sources of random microwave bursts. These sites are the probable location of black holes. Discovering radio bursts from globular clusters would, thus, contribue much valuable information to the understanding of stellar and galactic evolution.

Since the radio pulses are probes of the material through which they pass, the environment around the potential source of pulses within a globular cluster can be studied. The distortions imposed on a pulse reveal the nature of the distortion mechanism. So, just as in case of the pulsar signals, the bursts from a globular cluster can be used to examine material in the vicinity of the source, and provide evidence that perhaps the source is indeed a black hole.

References

Hawkins, T.H., 1975, Methods in Computational Physics, 14, Academic Press.

APPENDIX A

DUDLEY OBSERVATORY REPORT NO. 10

DUDLEY OBSERVATORY REPORTS

A FAST FOURIER TRANSFORM SPECTROMETER WITH APPLICATIONS IN RADIO ASTRONOMY

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Report No. 10
October, 1975

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A FAST FOURIER TRANSFORM SPECTROMETER

WITH APPLICATIONS IN RADIO ASTRONOMY

Ivan R. Linscott, Joseph W. Erkes, Noble R. Powell

Abstract

A coherent radio-frequency spectrometer, based on the fast Fourier transform (FFT) method, has been designed to study a large class of astrophysical phenomena with higher sensitivity and resolution than is provided by present instrumentation. These phenomena are the sources of highly transient coherent microwave radiation, such as pulsars and supernovae. To probe the nature of these sources a signal processing system is needed with an on-line ability to remove the effects of (often unknown) dispersion distortion in real-time, over a broad frequency band, with a large dynamic range. This spectrometer system will operate in real-time for a 10MHz bandwidth by directly calculating, via digital techniques, a 10 bit, 1024-point spectrum in 0.1 millisecond, in either the frequency or dispersion domain. The spectrometer will perform predetection dispersion removal flexibly in real-time by the on-line modification of the Fourier transform's trigonometric weights. With coherent signal processing, the sensitivity of this spectrometer to broad band pulses distorted by large dispersions is over 100 times greater than the multi-filter compression techniques. This spectrometer improves the time resolution for dispersion-removed signals by nearly 100 times over present instrumentation. Thus coupled with an even modest-sized radio telescope, this FFT Spectrometer may be used to examine pulsar micro-structure, study pulsar emission mechanisms and the interstellar medium, and search for supernova events and other radio bursts.

Introduction

A new, high resolution, general purpose radioastronomical instrument is described that has direct application to the study of short-time constant phenomena and the potential to reveal new structures in astrophysical processes. The field of short-time constant astronomy has been largely unexplored due to the lack of adequate instrumentation and the inclination toward increased integration times (Cavallo 1973). As pointed out by Bondi (1970), this trend has almost excluded the study of transient effects and perhaps "we are missing a whole continent."

This instrument is a coherent spectrometer based on very recent advances in high-speed digital electronics technology (Powell 1974). Using these digital techniques to implement the fast Fourier transform (FFT) method in hardware, the spectrum of microwave signals may now be computed in real-time in a bandwidth of $\geq$ 10 MHz. By maintaining coherence in signal processing, pre-detection dispersion removal may also be accomplished in real-time by operating the spectrometer in a mode set for either a specific dispersion or a mode covering a broad range of possible dispersions.

In section II the properties of the FFT Spectrometer are compared to the capabilities of some familiar spectroscopic instruments and techniques. In section III the design of the FFT Spectrometer is discussed, and in section IV some applications of the FFT Spectrometer are briefly mentioned.

Section II - Alternate Approaches

Many alternate approaches to the problem of transient radio spectroscopy are possible, but the direct computation of the Fourier amplitude by a real-time, coherent system provides such a powerful analytic capability that the FFT Spectrometer is generally superior to these other methods. Table I summarizes the features of some familiar spectroscopic instruments and techniques. These

alternate approaches will be briefly discussed and compared to the capabilities of the FFT Spectrometer.

Instrument	Cost/Channel ($estimated)	No. of Channels (Typical)	Real-Time Pre-detection Dispersion Removal	Dynamic Range	Sensitivity (relative)	S/N Gain After Dispersion Removal	Frequency Spectra Rate (m sec.)	Band Pass (MHz)
Digital:								
FFT Spectrometer	$10	1000	easy	$\geq$ 1000	1	$\sqrt{Bt_s}$ ~1000	0.1	10
Autocorrelator	$10	1000	difficult	~ 10	~ 0.67	1 (no removal)	1000	10
Commercial Hardwired FFT	$50	1000	software	1000	1	$\sqrt{Bt_s}$ ~ 25	4	0.25
Analog:								
Bragg Cell	$10	1000	difficult	$\leq$ 0.1	1	$\sqrt{n}$ ~ 30	1	100
Light Valve	$100	1000	difficult	< 10	1	$\sqrt{n}$ ~ 30	1	10
Multichannel Filters	$150	50	difficult	1000	1	$\sqrt{n}$ ~ 7	fast	no limit
Swept Frequency Spectrometer	cheap	1	none	1000	inverse to sweep speed	1 (no removal)	variable	no limit

TABLE I

Radio-Frequency Spectrometer Characteristics

II.1 - Alternate Digital Systems

Autocorrelation spectrometers typically use one bit by one bit or one bit by multibit correlation methods (Hagen 1973), and thus have intrinsically limited dynamic range. Furthermore, to obtain spectra from these autocorrelation functions, Fourier transforms must still be calculated. Even using modern high-speed digital computers, the conversion times are typically of the order of one second for a thousand-point transform. The FFT Spectrometer employs multibit by multibit processing which offers a considerable improvement in sensitivity over the existing schemes. Its principle advantage, however, is that it can produce a thousand-point frequency spectrum in a tenth of a millisecond in real-time -- over a thousand times faster than autocorrelation spectrometers.

The Fourier transform is a very flexible representation of the data.

Additional manipulation can, for instance, combine sets of transforms to produce power spectra with increased resolution, or compute the autocorrelation function.

The dispersion in frequency and time of signals that have propagated appreciable distances in the interstellar or interplanetary medium can be quite serious for transient microwave radiation (Hankins 1971). The effects of dispersion on these signals may be compensated by an appropriate signal processing (Hankins 1971, 1972, 1973; Taylor 1974), and the sensitivity of the spectrometer improved. A pre-detection method of dispersion removal affords maximal improvement. For the autocorrelator, pre-detection dispersion removal in real-time involves passing the signal through a transversal filter before (or during) the autocorrelation function computation.

A transversal filter performs the dispersion removal in the time domain and consists of a tapped delay line along which the signal is propagated (Puckette et. al. 1974). Coefficient multipliers at each tap and an adder to combine the products complete the filter. The autocorrelator is then a special case of the transversal filter, and the dispersion removal could be done during the computation of the autocorrelation function (and vice versa) by a suitable processor design. This considerably increases the complexity of the autocorrelator system. For the FFT Spectrometer a simple modification of the FFT coefficients permits pre-detection dispersion removal at the same time that the Fourier transform is performed (see Section III for details), and thus requires little modification of the processor and no additional calculation time. Pre-detection removal can also be done for the autocorrelator system by further off-line software processing of the frequency spectra; however, since the autocorrelation spectra are sampled infrequently, little advantage accrues from such processing.

Commercial hardwired FFT's are available "off the shelf" for bandwidths up to 250 KHz. These are expensive and unsuitable for resolving sub-microsecond time structure like that present in some pulsar signals. Special designs, with increased speed, could be developed at much additional expense. What is required is an approach, described herein, by which the incremental cost per band is extremely small. The likelihood that an inexpensive commercial FFT of this nature will be available in the near future is very small.

A 10 MHz bandwidth could be analyzed by recording the microwave signals on, for example, several high-speed video recorders and then playing back the tapes at slower speed into a commerical FFT. This technique has no real-time capabilities and requires the storage of enormous quantities of data. Each hour of continuous recording would require forty hours of continuous processing through the commercial FFT. To store the data requires recording at the rate of 20 million words per second (200 Mbit/sec) and an hour's recording would generate the equivalent of 540 standard computer tapes.

Special purpose equipment, such as the Digital Pulsar Processor (Boriakoff 1973), has been developed with selected features of the FFT Spectrometer. For example, the Digital Pulsar Processor can perform on-line post-detection dispersion removal over 19 x 20 KHz band, but requires hardware changes to do pre-detection dispersion filtering.

II.2 - Alternate Analog Devices

The ability of a lens to take a Fourier transform has been exploited in the development of fast optical Fourier transform processors. The Bragg cell relies on the acoustic modulation of a surface to produce the object pattern for the transforming lens (Welsh 1974, Cole & Ables 1974) while the Light Valve constructs the object pattern from a video image (Noble 1974). Both techniques are capable of processing large bandwidths, but suffer from

possessing a limited dynamic range. For the Bragg cell the signal-to-noise S/N has an upper bound of $S/N \leq 0.1$, and for the Light Valve $S/N \sim 3$. A system designed to study transient radiation, especially signals received from coherent sources, will need a large dynamic range. For instance the microstructure in some pulsars has $S/N \sim 100$ (Hankins 1971), but the widths of the micropulses are as yet unresolved. Since the FFT Spectrometer will improve the time resolution by nearly two orders of magnitude, the dynamic range will probably become much larger, with the S/N approaching 1000. This calls for a 10 bit word size in the FFT processor, well within the capabilities of the proposed approach. Pre-detection dispersion removal would be difficult for these optical techniques since the focal length is a function of the dispersion, and responding to change in the focal length is a delicate mechanical problem (Noble 1974).

Multichannel filter systems are in common use as spectrometers. Aside from being expensive and tedious to maintain, incorporating pre-detection dispersion removal into the system requires a steady phase-locked coherence over many bands and is a major job. The resultant system would contain a device at least as complicated as a FFT processor in addition to the filter bank. Post-detection dispersion removal is easier, using pulse compression techniques, for a filter bank but the increase in sensitivity is $n^{1/2}$ (see Section III.3), where n is the number of channels in the system, and does not depend on the dispersion. However, pre-detection dispersion removal increases sensitivity by $(B\tau_s)^{1/2}$ (see Section III.3), where τ_s is the pulse sweep-time across the band B, and does depend on the dispersion. So for pulses with large dispersions and standard filter banks ($\tau_s \sim 0.1$, $n = 50$, $B = 10^7$ Hz), the pre-detection dispersion removal technique makes the FFT Spectrometer $\gtrsim 100$ times as sensitive as the post-detection pulse compression techniques.

Further improving the sensitivity of the post-detection method by including a large number of additional channels is unsatisfactory because the noise over the whole band also increases as additional filters of finer resolution are added.

Swept frequency spectrometers are accurate, inexpensive and capable of observing enormous bandwidths. However, the rate at which they may be swept is inversely related to the square of the required resolution. So, for observing transient signals received at arbitrary times at arbitrary frequencies over large bandwidths, such as flare events, a swept frequency system is of no use. However, the FFT Spectrometer can continually monitor a large bandwidth; thus, aperiodic transients are detectable.

In summary, the FFT Spectrometer is the only instrument that incorporates into one system all of the following features: (1) pre-detection dispersion removal, (2) large dynamic range, (3) real-time signal processing, (4) coherent signal processing, (5) large bandwidth, (6) high resolution, (7) high sensitivity, (8) general purpose application, and (9) low cost. The FFT Spectrometer has been designed for the study of a number of currently interesting astrophysical problems including pulsar spectra, interstellar dispersion, black hole structure, flare phenomena and searches for extra-terrestrial intelligence. Equally important is the potential of the device for uncovering transient phenomena as yet unknown. Thus the FFT Spectrometer, coupled with a dedicated high-speed minicomputer can be used for real-time analysis of a wide variety of transient electromagnetic phenomena.

The FFT Spectrometer signal processing system will be described in detail in the following section. Special attention will be paid to the design of the FFT processor and the on-line data processing capability.

Section III - Signal Processing System

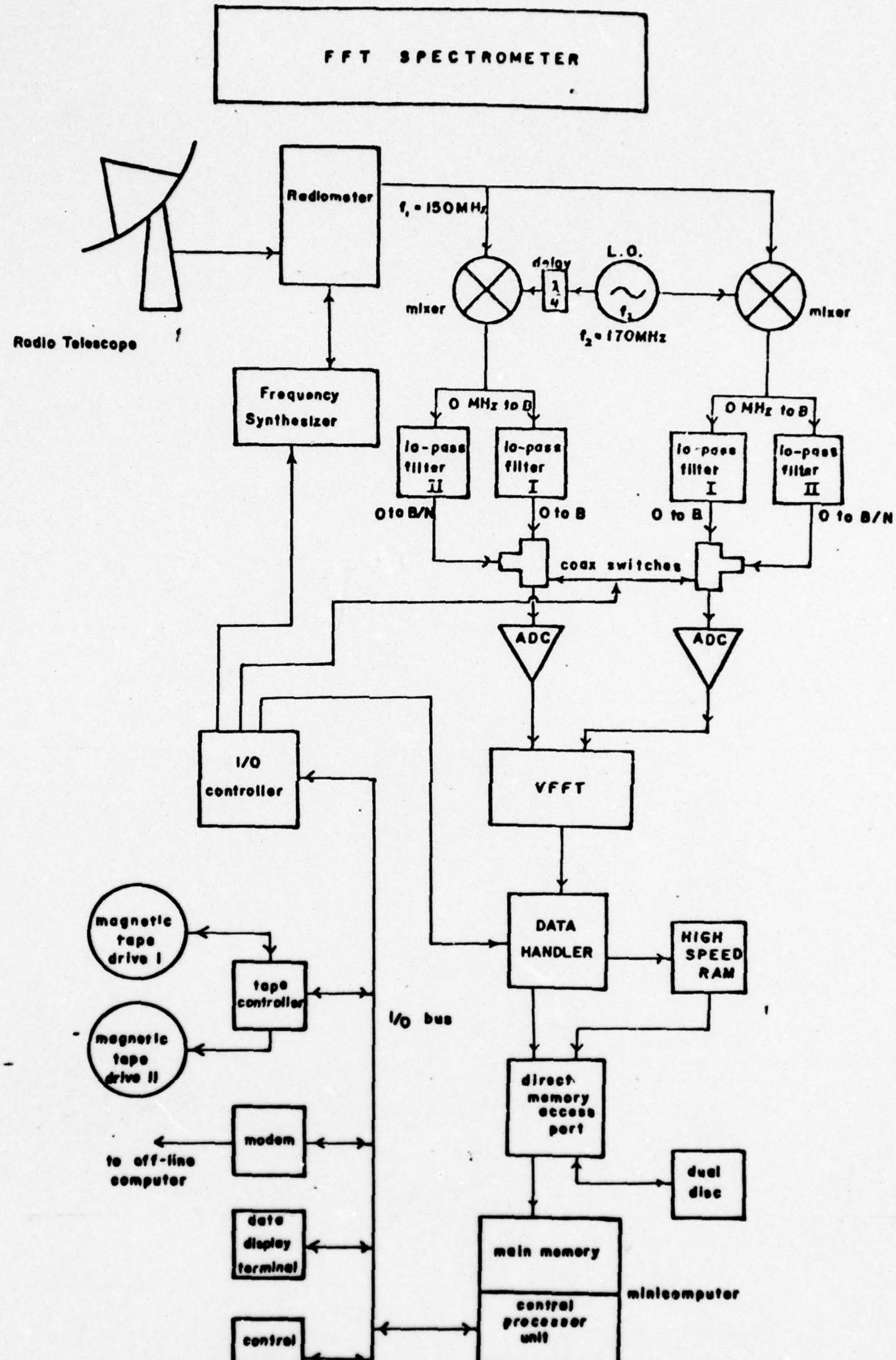
III.1 - The FFT Spectrometer

The FFT Spectrometer is a coherent receiver designed to analyze the time and frequency structure of transient microwave radiation in a 10 MHz bandwidth. Maintaining coherence and using Fourier amplitudes to represent the data affords many advantages for signal processing. One such advantage is the ability to perform pre-detection dispersion removal. This technique provides a significant increase in the sensitivity of a spectrometer to transient signals over post-detection dispersion removal methods. In fact, many of the analytic methods which have been successfully applied to the processing of acoustical signals may now be carried over to microwave signals by using the FFT Spectrometer.

The design of this coherent signal processing system will be discussed in this section along with the design of the very fast Fourier transform (VFFT) processor which executes the Fourier transform at microwave speeds. Finally, the operating modes which produce the frequency spectrum and the dispersion spectrum will be detailed.

A block diagram of the signal processing system is shown in Figure 1. The data flow through the FFT Spectrometer system is as follows:

1. The RF signal from a radio telescope, amplified by a radiometer, is gated through to A/D converters, operating at $\sim$ 10 MHz, which sample both the in-phase and quadrature components.
2. The digitized signal is sent to the very fast Fourier transform (VFFT) processor, which produces 1024 channels of complex Fourier spectra in 100 microseconds. The coefficients of the VFFT processor can be adjusted so that the FFT computation also performs pre-detection dispersion removal. The VFFT processor is discussed in



FFT SPECTROMETER
Radio Telescope
Radiometer
f_1 = 150MHz
mixer
delay
$\frac{\lambda}{4}$
L.O.
f_2
f_2 = 170MHz
mixer
Frequency Synthesizer
0 MHz to B
lo-pass filter II
lo-pass filter I
0 MHz to B
lo-pass filter I
lo-pass filter II
0 to B/N
0 to B
0 to B
0 to B/N
coax switches
ADC
ADC
I/O controller
VFFT
DATA HANDLER
HIGH SPEED RAM
magnetic tape drive I
tape controller
magnetic tape drive II
I/O bus
direct memory access port
modem
to off-line computer
dual disc
data display terminal
main memory
minicomputer
control processor unit
control terminal

Figure 1

Section III.2.

3. The complex Fourier spectra are sent to a data handler. In the frequency spectrometer operating mode, the data handler computes a running variance, stores the spectrum temporarily, and sends the minicomputer a list of active channels. The data handler has a fast memory capacity for 100 spectra. In the dispersion spectrometer operating mode, the data handler reformats and accumulates the spectra. The reformatting and accumulation are discussed in Section III.3.

4. The data flow from the data handler to the minicomputer is under the control of the minicomputer, hence many operating conditions are possible.

One very important mode for the operation of the FFT Spectrometer is the active mode, in which it can respond to transient signals in real-time. As an example, when the power in any channel exceeds some threshold amount, set by the minicomputer on the basis of the running variance, a triggering algorithm running in the minicomputer can direct an on-line response. On-line responses include the following:

1. Freezing the contents of the fast memory in the data handler, after the transient has passed, and transferring the data into the computer for further analysis. If the transients are periodic, with low duty cycle, e. g. pulsars, the fast memory contains the pulse and the transfer can be accomplished between pulses. The spectra can be examined between pulses, if the computations are kept simple, to see if the pulse had any of a set of pre-determined characteristics, e.g. giant pulses. If the selection criteria are satisfied, the spectra are saved in the minicomputer. A subset of rare pulses

obtained this way would be useful in studying the mechanism of emission and dispersion. (See section on pulsar studies for specific criteria).

2. Stepping the Local Oscillator, (L.O.) to track a pulse as it sweeps in frequency, thereby increasing the bandwidth of the system.

Obviously many other triggering modes are available through software.

III.2 - VFFT Processor Design

The bandwidth, B, of the radio telescope amplifier and the integration time, t, for the signal together specify N, the number of samples that must be taken to obtain a faithful representation of the frequency spectrum, where

$$N = \frac{2.5}{2} Bt.$$

The sample rate is $f_s = \frac{2.5}{2}B$ if the signal is heterodyned down to base band (zero frequency at low end). The time, T, to compute the transform based on a radix-4 FFT algorithm is (Pease 1968, Sloat 1974),

$$T = \frac{2.5}{2} \frac{B}{2} t \, \tau \log_4\left(\frac{2.5}{2} Bt\right).$$

where τ is the computation time per operation. An additional factor of 1/2 has been included under the assumption that the complex operations are performed in parallel.

If B = 100 MHz, then f_s = 125 MHz. In the near future ADC's will likely be available which sample at rates $\geq$ 100 MHz, and an array processor could be built to perform the FFT in real-time (Sloat 1974). However, present economics and component availability suggest a sampling frequency close to 10 MHz. For these reasons, together with an abundance of astronomical applications, let B = 10 MHz, and N = 1024.

Recently a high speed, inexpensive, digital multiplier chip has been developed (Powell 1974) with τ = 0.5 microseconds/bit for the hardware real-

ization of FFT algorithms. Using this value for τ, the time to compute a 1024-point, 10 bit FFT is then,

$$T = 12 \text{ msec.}$$

Since the time to acquire 1024 points of sampled data at $f_s = 12.5$ MHz is,

$$t = 0.08 \text{ msec.}$$

the transform is being computed $T/t = 150$ times slower than the data are coming in. To increase the rate of the FFT computation, use is made of the symmetries inherent in the Fourier transform to separate the computation into two classes: those performed sequentially, and those performed in parallel. Then these two classes are appropriately organized so that $T \leq t$. Here, one typical organization, the serial processor, is considered.

III.2a - Serial Processor

For the purpose of parallel processing the arithmetic operations should be organized in as few levels as possible. Each level should involve a set of elementary operations that can be done simultaneously. Using the intrinsic symmetry of the Fourier transform, each level or stage of the FFT computation may be standardized (Pease 1968). In radix-4 the form of this standard representation is especially simple and is shown pictorially in Figure 2.

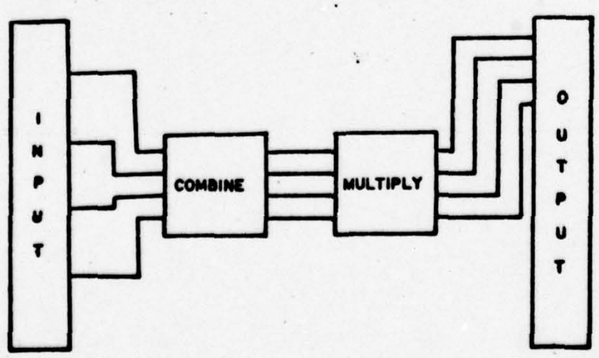


Figure 2
Radix-4 Form for One Level of the FFT Processor

The FFT is performed in a recursive method by:

1) Loading the sampled RF amplitudes into an input shift register

2) tapping the register in four non-adjacent places

3) shuffling the four data words to a standard order

4) multiplying the data by complex trigonometric weights

5) loading the processed words into consecutive positions in an output shift register

6) cycling the shift registers to process all words.

This now completes one stage of the FFT calculation. The remaining stages can be processed by either

1) Shifting the output back into the input register and repeating the above steps 1 - 6, or

2) Repeating the module of Figure 2 for each stage of the FFT computation.

The combine-and-multiply operation is performed using the new digital multiplier chip. A group of eight of these devices, appropriately interconnected will execute four complex combine-and-multiply operations. These monolithic computation elements (MCE's) require the data to be input in a bit-serial form and operate in the range of 2 - 3 MHz. The time required for the combine-and-multiply operation is about 5 microseconds for a 10 bit word.

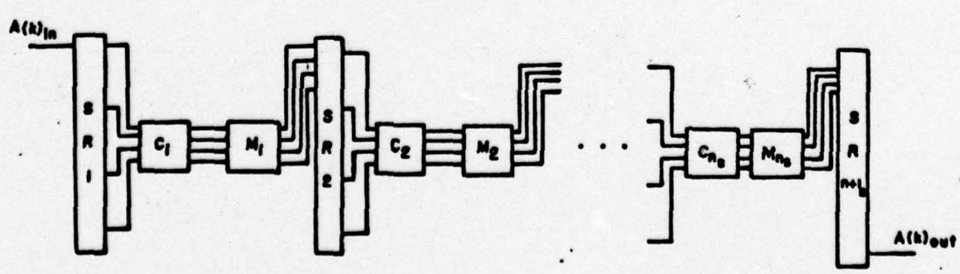


Figure 3
Radix-4 Pipeline Processor

The latter method (2), shown in Figure 3, allows the data to flow down a pipe with n_s stages, where $n_s = \log_r N = 5$, and is n_s times faster. To bring the speed of the FFT up to the incoming data rate, the shift registers are subdivided to allow many computations to be performed in parallel. In this case, a division of the shift registers into 30 identical sections, as in Figure 4, is necessary to match the rates.

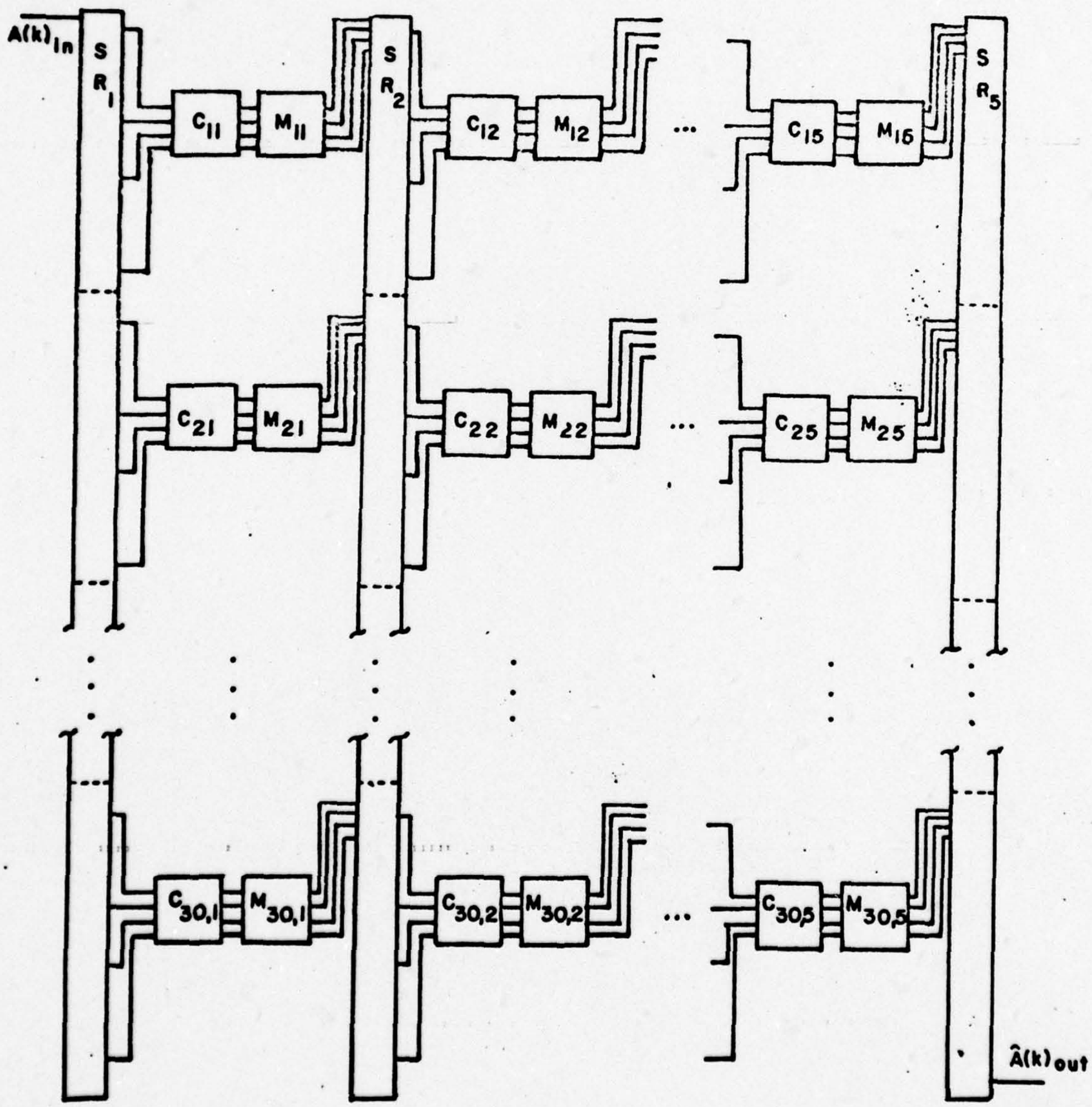


Figure 4
Radix-4 Parallel Pipeline Processor

This device is a very fast Fourier transform calculator, and requires,

$$n_c = 30 \times 5 \times \frac{8}{4} \times 2 = 600 \text{ MCE's.}$$

III.2b - Peripheral Interfaces

The accessory equipment needed to complete the FFT Spectrometer as shown in Figure 1 includes in addition to the data handler, signal interface components for the output of the radio telescope radiometer, data acquisition, modification, storage and display facilities, and also system timing and control circuitry. These components can be grouped into two functional stages, pre-processing and post-processing.

Preprocessing

The RF signal, prior to the FFT computation, is heterodyned down from a center frequency of 150 MHz using a frequency synthesizer under computer control. The center frequency may be changed in less than 1 msec. using a commercial synthesizer. A local oscillator, mixers, and a computer-operated coaxial switch together with the proper low pass filter complete the signal processing section.

Postprocessing

The problem of data storage is serious with data rates in the vicinity of 20 Mwords/sec. The postprocessing peripheral hardware has been designed to avoid storing voluminous amounts of data. Only a limited number of current spectra are temporarily stored in fast memory by the data handler. For each spectrum the data handler feeds salient features of the data to trigger algorithms in the minicomputer. The trigger algorithms are all in software and thus have much flexibility to look for specific or anomalous features in the incoming data. The data transfer rates are listed in Table II.

TABLE II

Data Transfer Rates

DMA Busses - 1.25 MHz byte-transfer rate (8 bit bytes)
Main Memory-Minicomputer Bus - 1.25 MHz transfer rate (8 bit bytes)
I/O Bus - 75 KHz transfer rate (8 bit bytes)
Data acquisition rate (VFFT rate) - 20 MHz transfer rate (8 bit bytes)
High Speed Memory (RAM or SR) - 20 MHz transfer rate (8 bit bytes)

III.3 - Operating Modes of the FFT Spectrometer

Frequency Spectrometer

In the frequency spectrometer operating mode the data handler approximates the power spectra from the absolute magnitude p_n calculated from the Fourier amplitude. The fast magnitude approximation is,

$$p_n = L_n + \frac{3}{8} S_n$$

where L is the larger of (x_n, y_n) and S_n is the smaller of (x_n, y_n). Here x and y are the real and imaginary parts of the Fourier amplitude in the n^{th} channel. This approximation is for triggering purposes only and does not affect the spectrometer's ability to detect large classes of transient signals.

A running variance is evaluated from the absolute magnitudes, and the list of active channels is derived from this reference. The software in the minicomputer can act directly on the frequency spectra stored in the short-term fast memory, thereby operating the spectrometer in a low duty cycle mode. Alternatively, the software can monitor the active channels while operating the spectrometer in a high duty cycle mode.

Dispersion Spectrometer

The FFT Spectrometer can be run as a dispersion spectrometer by applying an additional transform to the Fourier spectra in the following manner. The received signal, represented as a Fourier integral is

$$u(t) = \int A(\omega)\, e^{ia\omega^2} e^{i\omega t} d\omega$$

where $A(\omega)$ is the frequency spectrum, $\frac{d\omega}{dt} = \pi/a$ and $a \sim DM$. The Fourier transform of $u(t)$ is

$$u(\omega) = F_{\omega t}\left[u(t)\right] = A(\omega)\, e^{ia\omega^2} .$$

where F_{xy} denotes a Fourier transform and x,y are the conjugate variables. Now define $A'(y) = A(\omega^2)$, $y = \omega^2$, then perform another Fourier transform,

$$\tilde{u}(\epsilon) = F_{a'y}\left[u(y)\right], \quad \epsilon = a-a'$$

If $u(\omega)$ is a pulse spectrum, say $A(\omega) = \frac{1}{\sqrt{2\pi}} e^{-k^2\omega^2}$, then,

$$\tilde{u}(\epsilon) = \frac{1}{\sqrt{2\pi}} \frac{1}{(k^2 + i\epsilon)} .$$

In addition, if the pulse is "narrow", then $\tilde{u}(\epsilon)$ will be sharply peaked about $\epsilon = 0$ as shown in Figure 5. The dispersion transform will be useful

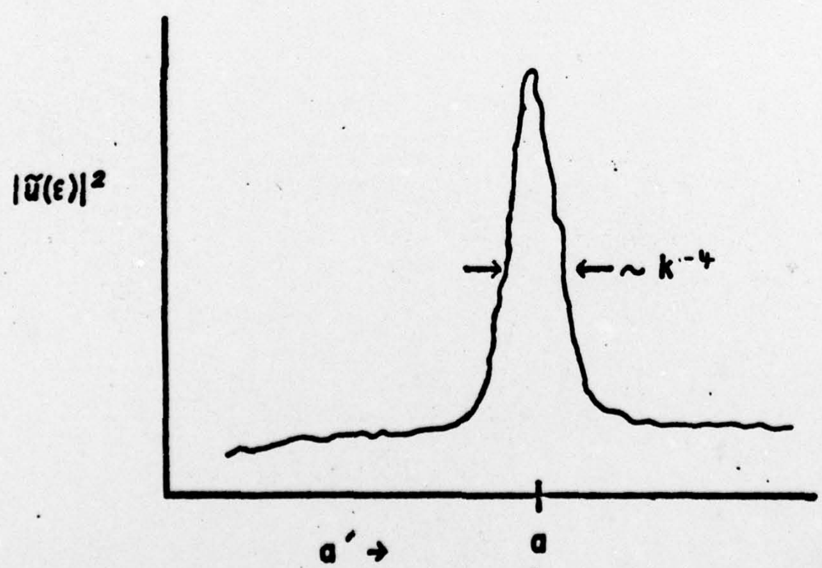


Figure 5
A Typical Dispersion Spectrum

when the pulse width has been appreciably broadened by dispersion distortion.

To operate in the Dispersion Spectrometer mode for high dispersion pulses, successive Fourier transforms will be accumulated by the data handler* as $A'(y)$ for say a 1 msec interval. Then the VFFT will calculate $\tilde{u}(\epsilon)$ from $A'(y)$ in the standard 0.1 msec. This imposes a 10% dead-time on the system. Longer accumulations will scale the range of dispersion and can be accomplished by calculations in the minicomputer. There is a trade-off between dead-time and the lower bound of the dispersion spectrum, which for high dispersion pulses is of minor consequence. For low dispersion pulses, each Fourier spectra computation could be followed by a dispersion spectrum transform. This would reduce the bandwidth by a factor of two. The low dispersion does not affect the signal strength nearly as much as high dispersion, and the normal FFT Spectrometer operating mode has a comparable sensitivity. For high dispersion however, the Dispersion Spectrometer mode affords an increase in sensitivity of perhaps several orders of magnitude.

The increase in sensitivity provided by dispersion removal techniques is largely the result of decreasing the pulse width in the receiver. The effect of a quadratic dispersion on a pulse is to sweep the pulse across the receiver bandwidth as shown in Figure 6. In one method of dispersion removal, the bandwidth is divided into many narrow bands, and the bands are added together, as shown in Figure 7, with an appropriate delay.

* Accumulation of Fourier spectra is accomplished by multiplying each channel in consecutive spectra by the phase $\exp(i\omega_n T)$, where ω_n is 2π times the frequency in the n^{th} channel, and T is the time interval between transforms. The consecutive spectra are then added together channel by channel. The phase multiplication can be done by the usual modification of the FFT's trigonometric weights.

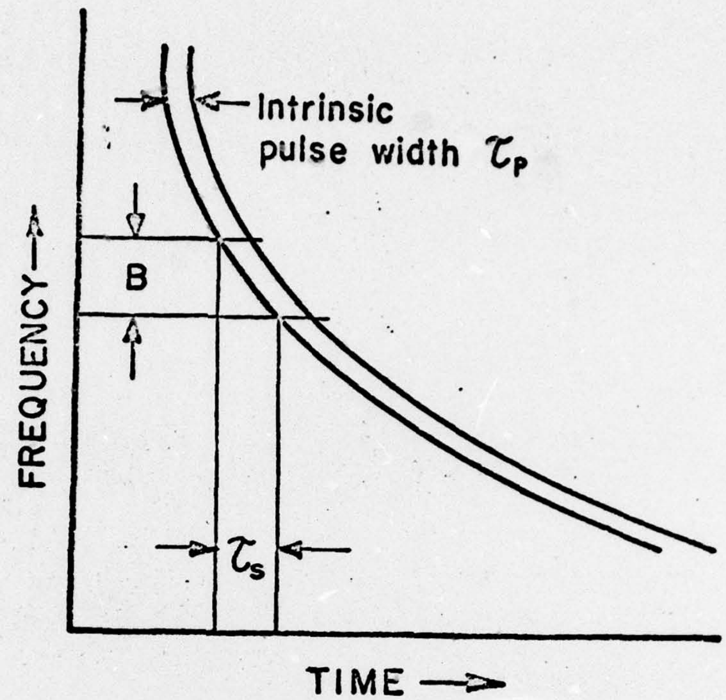


Figure 6
The Effects of Dispersion and Bandwidth on Pulse Width

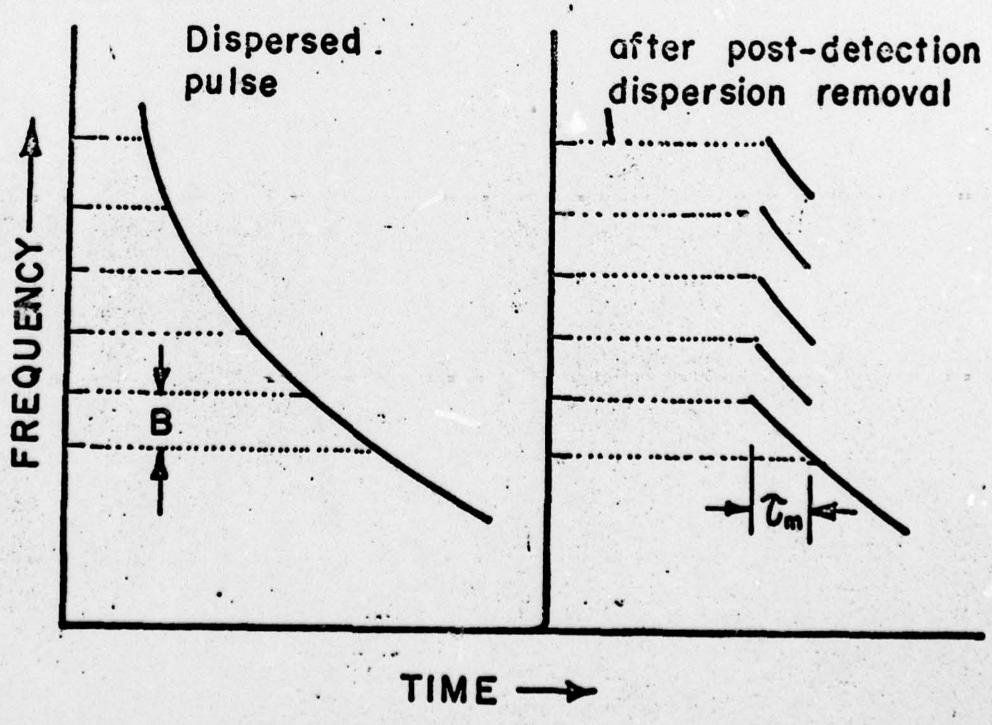


Figure 7
Post-Detection Dispersion Removal

In the case where no dispersion compensation is attempted, the signal-to-noise ratio for a pulse of strength S_o, dispersed over a bandwidth B of the receiver, in a time τ_s, is

$$\frac{S}{N}(\text{no compensation}) = \frac{S_o}{T_N} (B\tau_s)^{1/2}$$

where T_N is the receiver noise temperature. Now for the case where the dispersion is removed by post-detection delay compensation (Figure 7) the pulse width is shortened to $\tau_m = \tau_s/n$, where n is the number of filter channels. The signal-to-noise is thus

$$\frac{S}{N}\begin{pmatrix}\text{post-detection} \\ \text{dispersion rem.}\end{pmatrix} = \frac{S_o}{T_N}\frac{\tau_s}{\tau_m}(B\tau_m)^{1/2}$$

$$= n^{1/2}\,\frac{S}{N}(\text{no compensation}).$$

Thus the pulse compression post-detection dispersion removal technique is more sensitive to a dispersed pulse than the conventional uncompensated receiver by a factor of $n^{1/2}$.

The effects of dispersion may also be compensated for by pre-detection signal processing, as described for the Dispersion Spectrometer operating mode. In principle, using pre-detection dispersion removal, the original pulse width may be recovered up to bandwidth limit, $\tau_{min} = 1/B$ (see Figure 8). In this case, the signal-to-noise ratio is

$$\frac{S}{N}\begin{pmatrix}\text{pre-detection} \\ \text{dispersion rem.}\end{pmatrix} = \frac{S_o}{T_N}\frac{\tau_{min}}{\tau_s}(B\tau_{min})^{1/2}$$

$$= (B\tau_s)^{1/2}\,\frac{S}{N}(\text{no compensation}).$$

Thus, the pre-detection dispersion removal technique improves the signal-to-noise ratio by a factor of $\sqrt{B\tau_s}$. For broadband pulses ($B_{pulse} \sim B_{system}$)

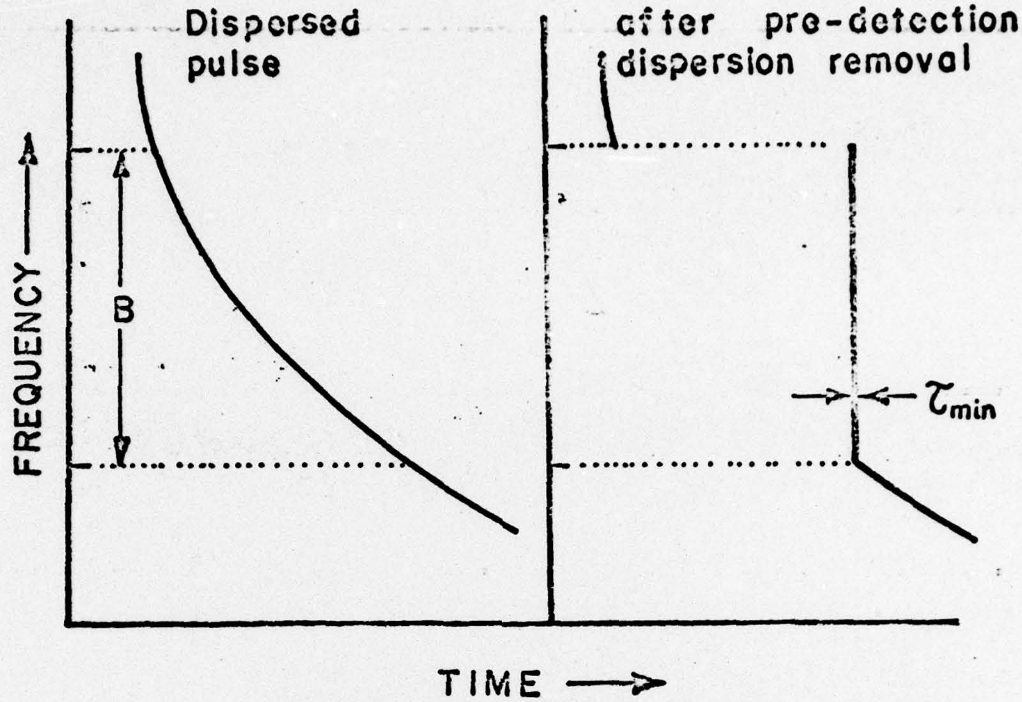


Figure 8
Pre-Detection Dispersion Removal

which have suffered large dispersions, pre-detection dispersion removal considerably increases the potential sensitivity over post-detection techniques, and conventional receivers. Typically for these pulses $\tau_s \geq 0.1$ sec., corresponding to a dispersion measure (DM) of ~ 30 at 400 MHz. The pre-detection dispersion removal method of this spectrometer is, in principle, 1000 times more sensitive to these pulses than conventional receivers, and over 100 times more sensitive than the post-detection delay compensation technique.

III.4 - Signal Processing System Summary

The signal processing system has been designed to handle high data rates and extract transient phenomena. The sheer volume of data collected during the observation of radio sources at 10 MHz bandwidth is such that

real-time analysis is essential in order to keep the total amount of stored information within reasonable bounds. The high and low duty cycle operating modes, as well as the fast frequency and dispersion spectrometer operating modes, have direct applications in experimental programs.

IV - Application of the FFT Spectrometer to Problems in Radio Astronomy

The FFT Spectrometer's ability to obtain a wide band, coherent, de-dispersed frequency spectrum in real-time, makes it a general purpose instrument with much flexibility. These features make it the best instrument for studying many problems in radio astronomy and astrophysics, and in fact it is the only instrument presently capable of investigating some of these problems.

Many radio sources emit coherent radiation (e.g. pulsars, the sun, radio stars, quasars, maser clouds) often with a time-varying structure. For some coherent sources, for example pulsars (Hankins 1971, 1972, 1973), solar flares, flare stars (Hjellming 1974), the time structure is finer at radio wavelength than the best available resolution of present instrumentation. For coherent radiation in the range of 100-1000 MHz, time structures shorter than 10 microseconds are known to occur. These observational results are not unexpected since coherent radiation can plausibly be argued to possess submicrosecond time structure.

Coherent electromagnetic radiation is usually the result of an ensemble of individual emitters radiating in phase with respect to each other. In the absence of a highly structured environment, or one possessing a high degree of symmetry, the size of the ensemble is, likely, of the order of the wave-length of the radiation. The duration of the coherent pulse is determined by how long the common phase of the emitters in the ensemble is maintained. The common-phase emission time is, likely, of the order of the transmit time

for the radiation across the ensemble. For a pulse of coherent radiation with peak power at 100 MHz, the pulse duration would be expected to lie in the range 0.01 microsecond to 1 microsecond. It is plausible, then, that coherent microwave radiation has submicrosecond time structure. Hence the strength of signals from coherent sources after dispersion removal may be many orders of magnitude greater than the strength measured using the relatively long time constants of present instrumentation. Pulsar signals (Hankins, 1971, 1972, 1973) certainly support this scenario.

Pulsar Studies.

The radio signals received from pulsars are distorted by the interstellar medium. Plasma dispersion is the principal form of distortion and is particularly severe at meter wavelengths (Taylor & Huguenin 1971). This dispersion is easily measured and can therefore be removed by applying the appropriate transform to the received signal. By receiving the signal coherently, the dispersion removal may be included in the Fourier transformation, thus permitting the undispersed pulse spectrum to be obtained in real-time.

For some pulsar signals the removal of dispersion has revealed a rich microstructure (Hankins 1971) (Boriakoff, 1973). Many subpulses have strengths in excess of 10^4 Janskys*, and occasional micropulses have strengths above 40,000 f.u. These results are from the observations of CP0950 and CP1133 at 111.5 MHz with a bandwidth of 125 KHz. As Figure 9 shows, the strength of those micropulses is a linear function of the smoothing time, and even at the highest resolution the strength is still increasing. By extrapolating the data shown in Figure 9 to 0.1 microsecond, (the resolution of the FFT Spectrometer) signal strengths of the order of 10^5 f.u. would be expected. Scintillation in the interstellar

* 1 Jansky or flux unit (f.u.) = 10^{-26} watts $m^{-2}Hz^{-1}$

medium will generally broaden these pulses, effectively limiting the bandwidth. The data in Figure 9 suggest however, that this limit has not been reached.

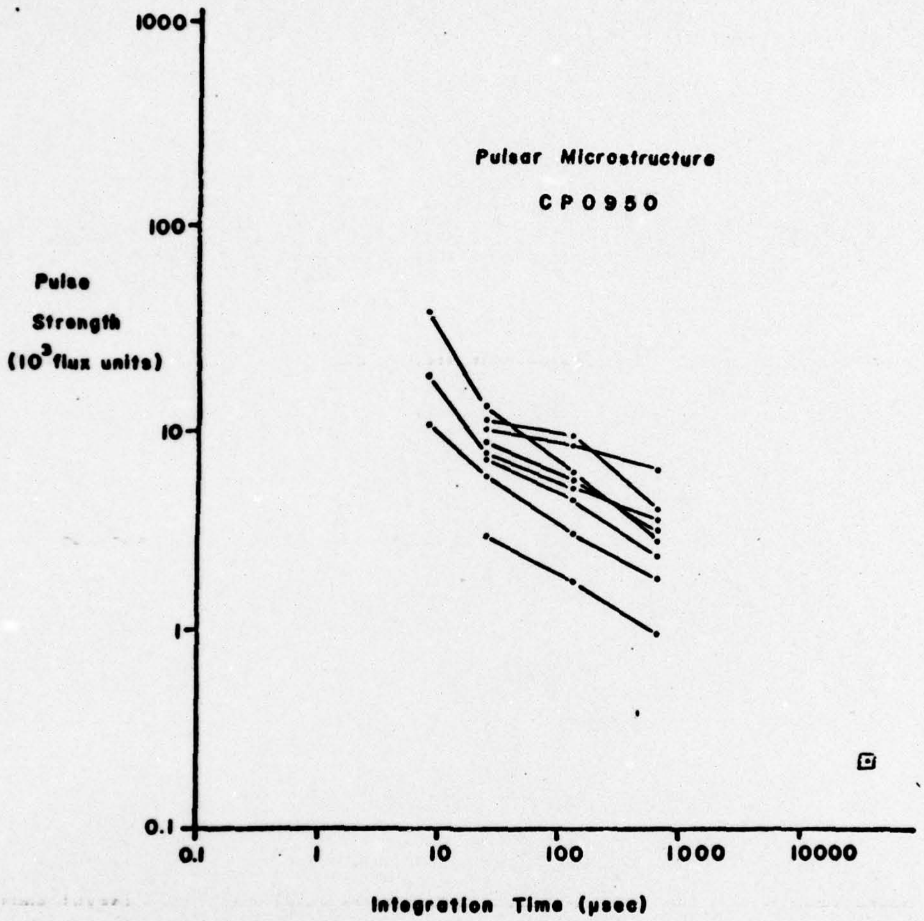


Figure 9
Micropulse Strength as a Function of Smoothing Time

The effect of dispersion is to sweep the pulse through the receiver bandwidth with a rate inversely proportional to the dispersion measure

$$\text{Sweep rate} = \frac{df}{dt}$$

$$\left.\frac{df}{dt}\right|_{f_o} = \frac{4\pi^2\, mC\, \epsilon_o f_o}{e(DM)} \; .$$

Under appropriate conditions, the center frequency of the receiver, or the mixer IF frequency, could be moved to track the pulse through a much larger bandwidth. If the sweep time $\tau_s = B/\frac{df}{dt}$ is greater than the pulse width τ_p, the whole pulse may be tracked, while for $\tau_s < \tau_p$ the tracking will sample only a fraction of the pulse.

This technique effectively increases the system bandwidth perhaps 10 to 100 times, improving still further the signal/noise. The L.O. is under computer control, so if the on-line program spots an interesting feature, the computer can step the L.O. and thus track the signal through many bandwidths.

Supernova Detection

The supernova process is expected to produce a powerful pulse of coherent electromagnetic radiation (Colgate 1971, 1972). This pulse would have a total energy of $\approx 10^{41}$ ergs, with a shape and frequency spectrum as indicated in Figure 10.

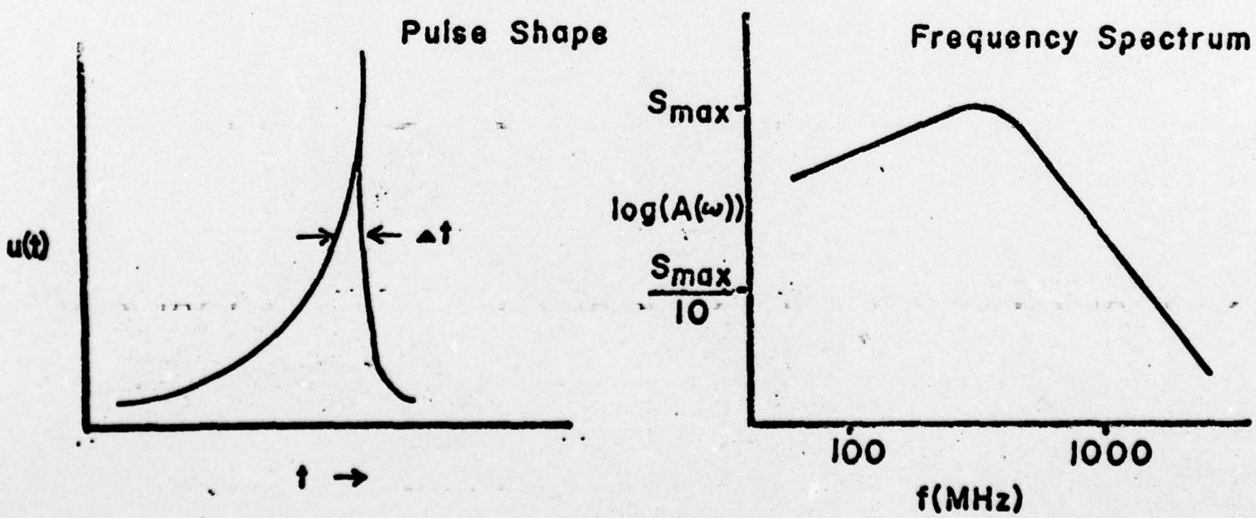


Figure 10
Predicted Shape and Frequency Spectrum for a Coherent Supernova Pulse

The supernova flash has never been identified in the radio spectrum. Coherent detection of such a pulse would provide detailed information on the supernova process, as well as the character of metagalactic space.

Detection of these pulses is complicated by the fact that supernovae occur at the low rate of 10^{-2} yr.$^{-1}$ galaxy^{-1}, and the pulse is distorted by the dispersion and scintillations of metagalactic and interstellar space. Hence a large number of galaxies should be continually monitored by a system capable of on-line dispersion removal for a wide range of dispersion measures. Moreover, each dispersion measure in this range should be monitored on-line. We call such a system a Dispersion Spectrometer and note that it is one of the operating modes of the FFT Spectrometer.

The detection of coherent pulses from supernova by a Dispersion Spectrometer is accomplished as follows: Assume the Dispersion Spectrometer is used in conjunction with a high gain antenna.

Point the radio telescope in a direction of high galactic density such as the Virgo cluster. For a system sensitive to pulses from 100-1000 Mpc, then $\sim 10^4$ galaxies will be in the beam and ~ 1 supernova pulse day^{-1} will be detected.

To assess the Dispersion Spectrometer's sensitivity, consider a coherent pulse of $\sim 10^{41}$ ergs generated by a supernova event at a distance of 100 Mpc. On arrival, the pulse will have a total energy of $\sim 10^{-9}$ ergs m^{-2}, and be dispersed by an unknown but presumably large amount. At this distance $\int n_e dl \approx 10^{20}$ cm^{-2}, or DM = 30, (Colgate 1972) and the frequency sweep rate is $\frac{df}{dt}$ = 10 msec/MHz at f = 400 MHz. Scintillation has broadened the pulse by an additional amount, Δt. If the pulse broadening of the Crab is typical for the interstellar medium, $\Delta t_s \approx 10^{-3} (f/230 \times 10^6)^{-4}$ sec. The intergalactic medium presumably broadens the pulse by a lesser amount.

The strength of the received pulse after dispersion removal as a function of frequency is shown in Figure 11, for various initial widths. These strengths are scaled by the frequency dependence of Colgate (1971) and include the effect of scintillation broadening.

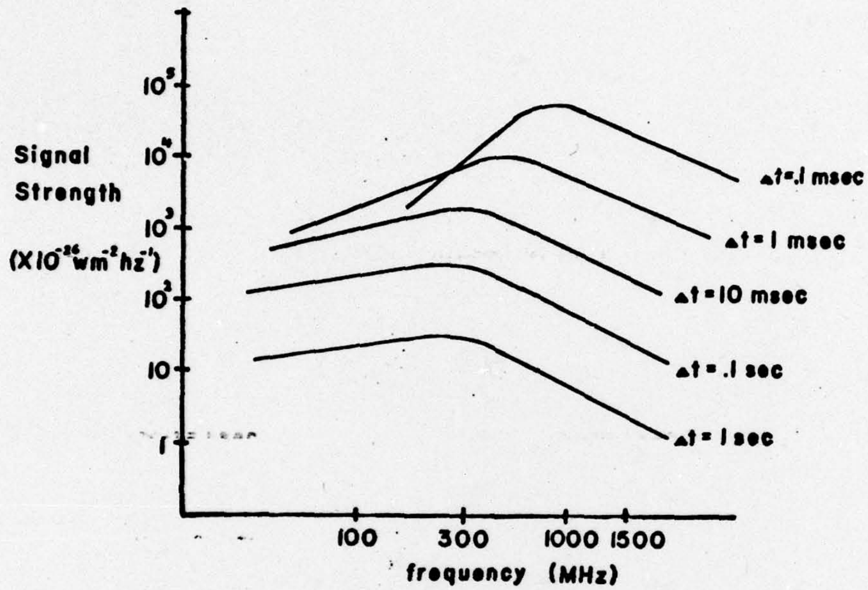


Figure 11
Restored Pulse Spectrum after Dispersion Removal

The signal-to-noise level in the receiver can be appraised by estimating the pulse energy and width, and the system noise temperature. A coherent pulse from a supernova with an initial energy of 2×10^{41} ergs, distributed over a sphere of 100 Mpc radius, has an energy density of $E_p = 1.7\times10^{-9}$ ergs m^{-2}. The pulse is distributed over a bandwidth of $B_p = 0.5$ GHz, according to Colgate (1972), and has a time duration in the receiver of $\tau = t_{pulse} + \Delta t_s$, with 0.001 sec. $\leq \tau \leq$ 1 sec. a likely range. At 400 MHz the combined system plus sky noise temperature is typically $T_N = 350$ ^oK, and the fluctuations in signal strength are

$$\Delta S_{RMS} = aT_N / \sqrt{Bt_{int}} \text{ watts } m^{-2}Hz^{-1},$$

where a ≅ 8 f.u./°K for a 100-ft. radio telescope, B is the system bandwidth, t_{int} is the integration time, and 1 f.u. = 10^{-26} watts m^{-2} Hz^{-1}. The signal-to-noise level for the received supernova pulse, after dispersion removal is then,

$$S/N = \frac{E_p}{B_p \tau} \frac{\sqrt{Bt_{int}}}{\sqrt{aT_N}} .$$

The Dispersion Spectrometer can approximately match the dispersion-removed pulse width to the integration time, so

$$S/N = \frac{E_p}{B_p a T_N} \frac{\sqrt{B}}{\sqrt{\tau}}$$

or, $34 \leq S/N \leq 3400$ for τ in the range 1 sec $\geq \tau \geq$ 0.1 msec.

Thus the Dispersion Spectrometer operating mode should easily detect coherent supernova pulses out to a distance of ~ 100 Mpc (~ 1000 Mpc if the pulse width is ~ 10 msec.). To detect one event day^{-1} about 4×10^4 galaxies should be in the beam. At 400 MHz the beam width of a 100-ft. radio telescope is 2°, and one supernova event day^{-1} will be detected at a level of $S/N \geq 3$ if $\tau \leq 1$ sec. and the average galactic density in the beam is $\rho_G \sim 0.5$ Mpc^{-3}. Similarly, one event day^{-1} will be detected at the same level if $\tau < 10$ Msec. and $\rho_G \sim 0.05$ Mpc^{-3}.

Additional Applications

The capabilities of the FFT Spectrometer suggest its use in a number of other observational programs. For these cases, coherent microwave radiation and the expected microstructure would be identified and studied in solar bursts, radio stars, QSO's, black holes and radio bursts from the galactic center. In addition, the FFT Spectrometer's high frequency

resolution (~ 10 Hz by extended off-line processing) and high sensitivity to transient signals would be useful in a search for beacons and leakage radiation from extraterrestrial intelligent sources.

V - Summary

In conclusion, the FFT Spectrometer is a powerful instrument for use in the analysis of time-varying radiation. The spectrometer system provides a wide-band, coherent, dispersion-corrected frequency spectrum in real-time, and is a general purpose instrument with much flexibility. The system can also be operated as a dispersion spectrometer. These features make the FFT Spectrometer ideally suited to the study of galactic and extragalactic sources of highly transient coherent microwave radiation.

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